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Interglacials of the 41 ka-world and the Mid-Pleistocene Transition

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A defining feature of the Quaternary is the quasi-periodic expansion and contraction of major Northern Hemisphere ice sheets. Before ~1.25 million years ago (Ma), glacial-interglacial cycles appear symmetric with smaller ice volumes and a period of 41 thousand years (ka, Fig. 1). Between ~1.25 to 0.7 Ma, the Earth's climate underwent a fundamental change, the Mid-Pleistocene Transition (MPT), where the dominant frequency of climate cycles changed from 41 to 100 ka. A full understanding of these modes of variation and the cause of such a change occurring under a relatively similar orbital forcing is still missing. To advance this topic, the third QUaternary InterGlacialS (QUIGS) workshop gathered 29 delegates to review the current science of the 41 ka-world interglacials and the underlying causes of the MPT. The outcome combines information from paleoclimatic archives together with insights from ice-sheet and climate modeling, producing future research directions.

Interglacials of the 41 ka world

Based on published and emerging paleoclimatic records extending beyond the MPT, similarities and differences in 100 ka-world (post-MPT) interglacials were identified. In brief, the 41 ka-world (pre-MPT) interglacials are generally more symmetrical in benthic $\delta^{18}O$ records than post-MPT interglacials (Fig. 1). Interglacial values are similar but the duration of pre-MPT glacial terminations and inceptions can differ. The high latitudes are characterized by warmer oceanic and continental surface conditions during pre-MPT interglacials. While pre- and post-MPT glacial atmospheric CO_2 levels differ, boron isotope-based reconstructions suggest similar interglacial levels (Fig. 1). The relatively high pre-MPT glacial-interglacial CO_2 and sea-level variability is not yet simulated in modeling studies. Pre-MPT interglacials are characterized by a millennial-scale climatic variability but the presence of a bipolar seesaw mechanism at their onset, a key millennial-scale feature of the post-MPT interglacials, cannot yet be assessed.

Sea-level and ice-volume estimates, as well as most reconstructions of more regional climate and environmental patterns during pre-MPT interglacials, have large uncertainties and limited temporal resolutions.

To provide further insights on the nature of pre-MPT interglacials, we encourage future investigations to focus on generating high-resolution datasets across a time slab characterized by typical pre-MPT glacial-interglacial cycles i.e. from Marine Isotopic Stage (MIS) 42 to MIS 46. We hope also that this will generate interest within the modeling community.

The MPT and underlying causes

The MPT, referring both to the change in frequency and intensity of glacial-interglacial cycles between 1.25 and 0.7 Ma, is characterized by multiple events identified in ocean circulation intensity proxies. It is mostly considered to be either driven by (i) an atmospheric CO_2 concentration decline, triggered by weathering or enhanced ocean uptake and storage or (ii) the removal by glacial erosion of thick sediment (regolith), exposing a high-friction crystalline Precambrian Shield bedrock, which increases ice stability, and an attendant change in the ice-sheet response to orbital forcing. Modeling studies have not fully reconciled the "regolith" hypothesis and questions remain over the timing of the regolith removal and the consequent ice-sheet response.

Progression on the causes of the MPT requires obtaining additional CO_2 reconstructions with reduced uncertainties. Boron-derived CO_2 data are coherent with direct CO_2 measurements performed on 1 Ma-old ice samples (Fig. 1) but the drilling of an "Oldest Ice" core back to 1.5 Ma (Fischer et al. 2013) would offer a large increase in confidence about the evolution of the climate-carbon cycle interactions across the MPT.

An article summarizing the ideas about the MPT is being prepared. New data, modeling exercises and ideas emerging from them should appear in the next few years, and QUIGS will return to this topic during its second phase, starting in 2018.

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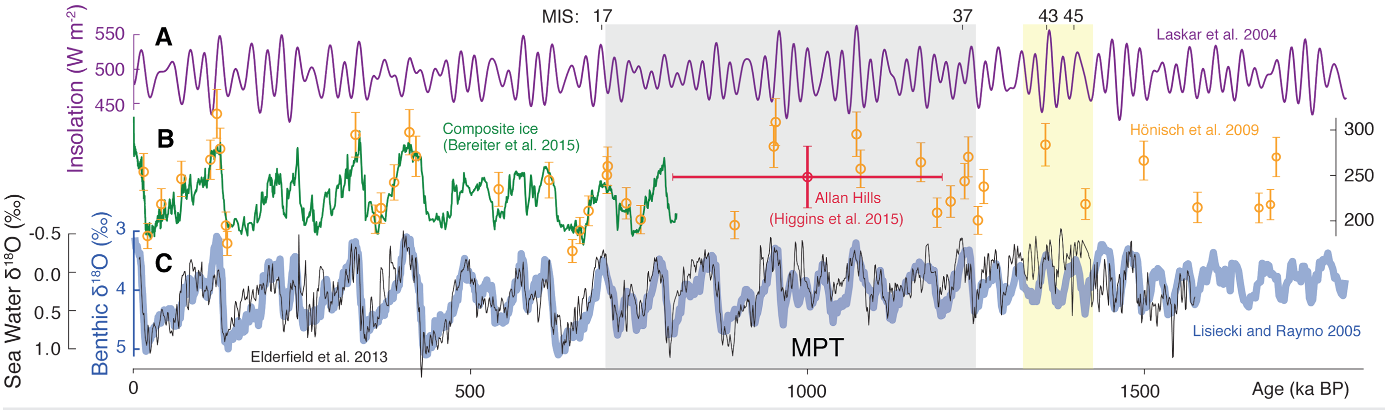

Figure 1: (A) 65°N summer solstice insolation, **(B)** Atmospheric CO_2 concentration, Allan Hills vertical error bars indicate 2σ spread with horizontal age uncertainty, **(C)** Global LR04 benthic stacked $\delta^{18}O$ (blue), ODP1123 seawater $\delta^{18}O$ (black). The MPT and the "typical 41 ka-world" intervals are highlighted in grey and yellow respectively.